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PROTON-BORON COLLIDING BEAMS FOR NUCLEAR FUSION *

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ABSTRACT

This paper describes a method of extracting energy from the fusion events occurring during collision of a beam of protons with a beam of ions of ^{11}B. The two beams circulate in separated and intersecting storage rings of the same geometry and size where they collide head-on in a common long straight-section. Requirements of the beam parameters and of the collider are presented and discussed for a total production of 10 kW of power. To allow small beam dimension and higher intensity, the storage ring itself is a novel concept based on a linear Radio-Frequency Quadrupole bent on itself and closed mechanically: the Circular RFQ. Stringent engineering limitations are encountered. Moreover, the collider performance is disrupted by Space-Charge forces, Intra-Beam and Beam-Beam Scattering. To alleviate and counter-come these limitations, the use of colliding Crystalline Beams is proposed. This has the benefit to enhance the Luminosity of the collision by several orders of magnitude. But it also requires fast and effective Laser and/or Electron Cooling. Sympathetic cooling of ions, as that demonstrated in ion traps, can also be used to avoid partially-stripped boron ions and negative-hydrogen ions.

CAUTION

This is an exploratory research of an advanced concept to produce Nuclear Fusion Power in modest amount. There are several technical issues involved that need to be discussed and studied in more details. This proposal requires the understanding of the state of the art of several technologies (accelerator, laser, beam cooling, crystalline beams and structures, ion traps, reactor engineering,...). For this project to succeed, one needs the pushing of the performance of some of the technical components beyond values already demonstrated. We may not have necessarily at this moment the answer to all possible questions. (If we did we would not be here, but probably sitting in a Company and selling these devices...!). Because of the so many technical features involved, and the different background of each of us, we might experience problems of communication and language. Nevertheless, we believe that this approach to produce Nuclear Fusion Power of modest amount is feasible and deserves to be explored further. Our proposal may need the solution of hard issues. But the amount of cost and effort to demonstrate whether the concept works is also very modest.

INTRODUCTION

The absence of an electric charge in a neutron makes it capable of interacting with very heavy nuclei and to cause their fission into two or more medium-size fragments with release of energy that can be converted to thermal and electrical power. Nevertheless, the presence of the neutron itself and of the fragments, that often have toxic properties, does not make this method of producing energy always appealing and useful.

On the other end, the presence of the Coulomb barrier between colliding light ions has been the major impediment for the practical application of nuclear fusion. In the past, several methods have been proposed and studied to generate and to control power from nuclear fusion. These methods, which are based either on magnetic or inertial confinement, require full-size and costly prototypes for demonstration. Even the simplest reaction considered, i.e., the fusion of deuterium with tritium, does not completely remove the presence of neutrons, and still requires the inefficient and elaborate conversion to thermal and electrical form of energy.

It has been suggested (Lidsky, 1983) that the fusion reaction between protons and ions ^{11}B is most desirable because of the complete absence of dangerous by-products; for instance, there is no neutron or gamma radiation involved. Moreover, it is possible to harness electric power directly from the reaction process because of very large charge state of the final product: three α particles. Unfortunately, this reaction exhibits a higher Coulomb barrier that requires larger energies of the colliding elements.

It was proposed (Ruggiero, 1992, 1993a, 1993b, 1998a) that the proton-boron reaction could be treated more easily with

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accelerator technology. A colliding beam scenario, based on the reaction between protons and ions of boron, has been proposed and investigated, but found to be seriously limited by space-charge forces and the Coulomb interaction among ions; i.e., the same forces which introduce the Coulomb barrier as the impediment to the two nuclei to fuse together. There is, thus the need to explore ways to overcome space-charge and Coulomb interaction effects if one desires to develop an energy device based on nuclear fusion.

One approach is the development of a novel concept of storage ring: the Circular Radio-Frequency Quadrupole storage ring (CRFQ) (Ruggiero, 1998b, 1998c, 1999a), which, contrary to more conventional magnetic rings, has the advantage to provide short focussing periods and thus very small beam dimensions. The CRFQ is an ordinary Radio-Frequency Quadrupole (RFQ) without vane corrugations, since there is no acceleration, bent and closed mechanically on itself, but open electromagnetic, acting therefore as a long transport. This device allows considerably higher beam intensity and density. The first part of this paper will deal with collision of ordinary "warm" beams of completely stripped ions (no electrons) circulating in CRFQ storage rings. Engineering limitations are met which can hardly be solved with the present state of the technology, and that can hopefully be deferred to a non-distant future. There are also physical limitations, again introduced by electromagnetic interaction among particles.

The limitations can be overcome by colliding Crystalline Beams (Wertheim, 1988, Montreux, 1993, Erice, 1995), an ordered state of matter which is made of a low-energy ion beam circulating in a storage ring where particles occupy rigid positions with respect to each other, essentially equally spaced. Particles are allowed only a small amount of kinetic energy variation from each other to maintain the amplitude of the oscillation smaller than the ion separation. It has been demonstrated that Crystalline Beams can be obtained in properly designed storage rings having a high degree of periodicity, smoothness, and compactness of focussing. The CRFQ storage ring is the ideal device also for this application. The use of colliding Crystalline Beams also enhances greatly the luminosity of the collision, and the requirement on the beam storage ring parameters become considerably less stringent. The idea of colliding Crystalline Beams is *per se* an interesting issue, which deserves further investigation. Fast and effective Laser Cooling is required for a beam to reach the ground state. This cooling technique requires either partially-stripped ions or negatively charged ions, so that electrons are introduced back in the collision with predictable consequences to beam stability and loss. Electrons can be removed by using fully-stripped ions by relying either exclusively on Electron Cooling or on Sympathetic Cooling (Mitchell, 1999) which has been successfully demonstrated recently in Ion Traps. A collider based on the use of Crystalline Beams is presented during the second part of this paper.

THE NUCLEAR FUSION PROCESS

An alternative method to fission reactors for producing nuclear energy is the fusion ot two very light ions. In principle, this process does not involve neutrons, and it is made possible by the fact that the average binding energy among the nucleons in the final product is higher than in the initial ions. An example involving the lightest ions is the fusion of deuterium and tritium. The ions have to collide at a sufficiently high energy in order to fuse, and the energy gain, the ratio of released energy-to-initial ion energy, is relatively lower when compared to the fission process. In the cited example, the energy gain is about sixty, since 17.6 MeV is the energy released and the colliding energy has a threshold value of about 300 keV. The cross-section, i.e., the probability of nuclear fusion, is also relatively lower when compared to the fission events. Nevertheless, the most crucial difference is that the two interacting elements of the fusion event carry an electric charge and that, in order to fuse, they have to penetrate the respective Coulomb barriers. Consequently, this requires larger colliding energies and yields a lower cross-section.

Nuclear fusion has now been studied for about half a century, with a considerable amount of human and financial effort; yet, practical solutions have not been demonstrated. The major impediment is indeed the presence of the Coulomb barrier, which has no equivalent in the exploitation of nuclear fission. The impediment can be understood by recognizing that electromagnetic interactions are at longer range and require a larger initial energy to bring the two ions closer to the point where the nuclear fusion forces are more effective. Several methods have been proposed and investigated. In some, the initial energy is obtained by heating up a plasma made of the ions involved (magnetic confinement); in others, the initial energy is obtained by imploding a mixture of the elements with pressure on an external shell generated by incoming intense ion beams (inertial confinement). Both methods have been found to be very expensive and require prototypes of full size for demonstration.

Historically, to circumvent the Coulomb barrier problem, the lightest ions, deuterium and tritium, have been taken as interacting elements in a nuclear fusion plant. Unfortunately neutrons are found again with the final products, the presence of which offsets some of the benefits of the fusion reaction. Moreover, the nuclear energy released, which has mostly the form of the neutron kinetic energy, has also to be thermally converted accompanied by a loss due to the lower conversion efficiency, as in the case of nuclear fission. Though there are obvious benefits in a nuclear plant based on nuclear fusion, because of the abundance of the primary elements and the lack of the medium-size fragments of toxic nature, we are still far away from a fully controlled and energy-effective demonstration. There is obviously need of studying different approaches.

THE FUSION OF PROTONS WITH IONS OF BORON

It has been suggested that a more advantageous method for obtaining and controlling nuclear power is the fusion between protons and ions of ^{11}B according to the reaction:

$$p \quad + \quad {}^{11}B \quad \rightarrow \quad {}^{12}C \quad \rightarrow \quad 3\,\alpha$$

Boron ions have mass number A = 11 and atomic number Z = 5. During the reaction the proton fuses with the ion, where it is trapped by the nuclear potential barrier. For a brief period of time, an ion of carbon ^{12}C is formed, with mass number A = 12 and atomic number Z = 6. The new ion is unstable and immediately breaks down in the three α particles.

In order for this reaction to occur, ions need a sufficiently large energy (Ajzenberg-Selove and Busch, 1980). There is a broad resonance centered around the center-of-mass energy of 675 keV with a width of about ±75 keV. This is followed by others in the few MeV range and preceded by one at 160 keV. The resonance at 675 keV is of particular interest: it exhibits (Becker et al., 1987) a large cross section $\sigma_F \sim 1.0$ barn. All other resonances either require a considerably larger energy or have lower fusion cross-section. The low energy combined with the relatively large cross section makes the reaction a good choice as a method for obtaining fusion nuclear power. Once the lowest bound state of the three α particles is reached, a total energy U = 8.7 MeV is released under the form of kinetic energy imparted to the α particles. The gain factor is Q = 13, lower than in the deuterium-tritium reaction, yet still appreciable.

Since it is relatively easy to control the energy of the protons and of the ions of Boron with accelerator technology, the fusion reaction here proposed can be easily ignited with no other possible channels of interaction involved. In particular no neutrons or gamma rays are produced, a fact that makes the process valuable for industrial applications. Another interesting feature is the large state of electric charge (Z = 6) of the final products that suggests methods for the direct conversion of the nuclear energy to electric power.

The major drawbacks of this reaction are the relatively higher initial energy required, the relatively lower cross section, and the higher charge state of the elements involved. The larger initial energy does not allow easily the use of methods based on the magnetic or inertial confinement. The energy of the beams, on the other end, is large enough for the application of accelerator technology.

The large charge state of the initial elements of course increases the effect of the Coulomb barrier. Since the charge state of the nucleus of Boron is 5, the height of the Coulomb barrier is also five times larger than in the case of deuterium colliding with tritium, which explains the need of commensurably higher initial energy. In colliding beams and accelerator technology, the effect of Coulomb interaction among ions is also referred to as Space Charge which is a serious limitation to the collider performance. These limitations are aggravated by the relatively lower cross section of the fusion events which requires larger colliding-beam intensities.

The method of colliding beams has been proposed earlier (Blewett, 1974, Maglich and Chang, 1993), but always in connection with the deuterium-tritium fusion reaction. It was always found, indeed, that space-charge limitations were too severe. Thus, in order to exploit the colliding beam method, it is crucial to find alternative ways to cope with the effects of Space Charge. These are: the CRFQ storage ring and Crystalline Beams.

In the plasma method, like a Tokamak, a two-component plasma (proton and Boron) is generated in a magnetic vessel and heated up to a very high temperature. The required spread is also about 675 keV, but the ions in the core of the distribution do not interact usefully with each other. Only those ions at the tails of the distribution can effectively fuse as shown in Fig. 1. Once they fuse, they are removed, and replaced by ions moving from the core and spreading toward the tail. This method then requires a considerable "hot" plasma with a very large ion volume density. In contrast, with the colliding-beam method, the two beams of proton and boron are constantly separated by an energy difference of 675 keV, have an internal considerable lower temperature, that is they are essentially "cold", and effectively fuse because they overlap in the same physical space of the collider.

Our goal is the demonstration of a modest power, e.g. 10 kW, as that required by a typical household in the USA. Aiming to a lower amount of power greatly reduces the range of the beam and collider performance and requirements, and makes the project more attainable, more economic, and less risky.

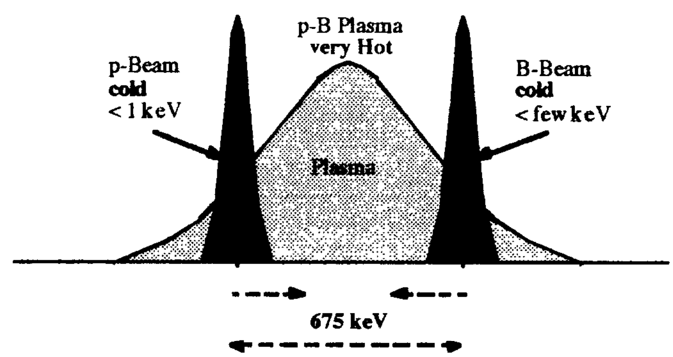


Figure 1. Energy Distribution in a Plasma and Colliding-Beam Methods

COLLIDING WARM BEAMS. AN EXAMPLE.

The layout of the device is shown in Fig. 2. There are two storage rings, which are taken to be identical in shape and size. The two beams of fully stripped ions of hydrogen H^+ and boron B^{+5} circulate in opposite direction, and collide head-on in a common Interaction Region. There are the following components: (1) a H^+ ion source which injects into the storage ring, and feeds continuously to re-supply the beam spent during the collision or otherwise lost; (2) a similar source of B^{+5}. It will be shown that, for a production of 10 kW of nuclear fusion power, the required ion source current is about 1.2 mA-particle, well within the capability of the technology available at the moment. (3) Two Circular RFQ storage rings, which here are assumed to be identical, and that will be described next. The storage rings are assumed to be identical with the beam energy adjusted so that they circulate with the same velocity and therefore revolution frequency. Of course other configurations are possible. We shall adopt the equal velocity configuration just as an example. (4) Collision of Ion Beams in the

Interaction Region. Finally, (5) The Reactor Vessel where the α particles are generated, collected, and electric power is generated. We will not discuss here the engineering details and requirements of the Vessel, except noting that it will likely be made of a sequence of electrode-grids placed at intermediate voltage. Electric fields decelerate the α's and current flows in an external load. The confinement of a 8.7 MVolt potential is not trivial. A lower voltage is more practical with the addition of an external solenoid magnetic field which will let multiple passages of the α's through the same decelerating electric field.

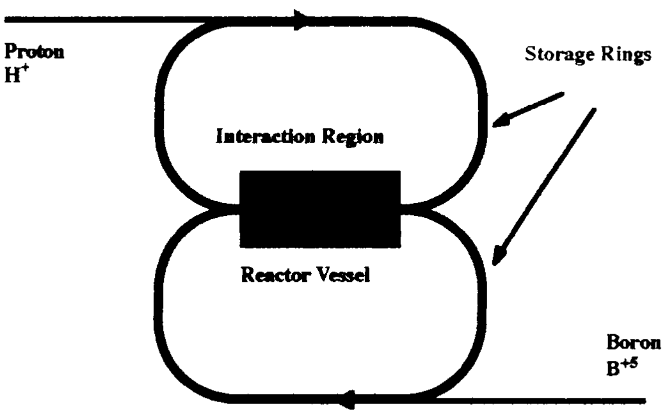


Figure 2. Colliding Beams Set-Up

To introduce the concepts involved in the device we shall consider an example, summarized in Table 1. First, we have assumed that both beams have velocity βc, and second, that the two storage rings have the same circumference $C = 2\pi R$. Also, we start with a large storage ring with circumference C = 100 m. We shall later consider storage rings of different size and work out the equivalent requirements. In any case, we shall consistently assume that the length ℓ of the Interaction Region is a fraction $\eta = \ell/C \sim 0.25$ of the circumference. Also, we shall require a total production of nuclear fusion power of 10 kW. It is our goal then to minimize the amount of power otherwise dissipated to only few kW. This should lead to a not-optimized conceptual design of an experiment for the demonstration of power production. Similarly, the principle of colliding beams need also to be demonstrated. Note that in this example of colliding "warm" beams, both are made of fully stripped ions, so that no electrons are involved. We shall use this example to estimate the design procedure and the requirements to attain the goal of 10 kW power. The procedure will then be used to investigate a broader parameter range.

COLLIDING BEAM LUMINOSITY

The geometry of the collision is shown in Fig. 3. The two beams have the same cross section $S = \pi a^2$, with a the average beam radius. They have a total number of circulating ions N_p and N_B. They collide head-on in the interaction region which has a length equal to a fraction η of the storage ring; and the common revolution frequency is $f_0 = \beta c/C$. The colliding beam performance is measured by the luminosity $\mathcal{L}$, also given in Fig. 3. When the luminosity is multiplied by the fusion cross section $\sigma_F \sim 1 \times 10^{-24}$ cm^2 it gives the number of fusion events per unit of time

$$dn / dt = \mathcal{L} \sigma_F \quad (1)$$

The fusion power generated is then

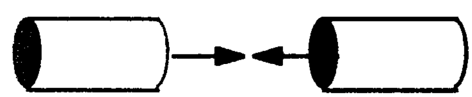
$$P_F = e U dn / dt \quad (2)$$

where U = 8.7 MeV is the energy released per fusion event. For 10 kW the required luminosity is $\mathcal{L} = 7.2 \times 10^{39}$ cm^{-2} s^{-1} corresponding to the rate of events $dn / dt = 7.2 \times 10^{15}$ s^{-1}. This is a very large luminosity compared to values that can be obtained in high-energy colliders. Nevertheless, the hope here is that this represents a very special low-energy collider where the conditions are more suitable for higher performance.

Table 1. Beam Parameters

	Proton H^+	Boron B^{+5}
Charge State, Z	+1	+5
Mass Number, A	1	11
Kinetic Energy, keV	56	619
β	0.01095	0.01095
Magnetic Rigidity, kG-m	0.343	0.754

We can also estimate the beam depletion rate $I_{pB} = e\, dn / dt = 1.15$ mA-particle, which is the current the ion sources are to provide to replenish the circulating beams at the same depletion rate. At the same time, the required beam power $P_{beam} = e\, I_{pB}$ (675 keV) = 780 Watt. The ratio $P_F / P_{beam} \sim 13$. All these quantities are constant and depend only on the wanted fusion power P_F.



$$\boxed{\mathcal{L} = \eta\ N_p N_B f_0 / S}$$

Figure 3. Colliding Beam Luminosity

To elucidate the procedure, we shall continue with our example by taking C = 100 m, from which f_0 = 32.8 kHz. A luminosity $\mathcal{L} = 7.2 \times 10^{39}$ cm^{-2} s^{-1} can be obtained, for instance, with $\eta = 0.25$, $N_p = N_B = 1 \times 10^{15}$, and a common cross section $S = 1.0 \times 10^{-6}$ cm^2. Obviously these are very high intensity beams, with very small transverse dimensions. Thus, the concern is the search and design of a storage ring that can indeed accommodate these values without encountering Space-Charge limitations.

Another quantity of relevance is the average time an ion spends circulating in the storage ring before it fuses

$$\tau \;=\; N_{pB} / (dn / dt) \qquad (3)$$

In our example τ = 140 ms. Any process other than fusion that may lead to a particle loss or an increase of the beam dimension, and thus to a lowering of the luminosity, can be described by a proper time that is to be compared to the fusion depletion time, and be sufficiently larger. That is, one has to insure, in the design of the collider, that ions have a good chance to fuse before they are removed by other effects like Coulomb scattering. Also, as ions are removed, they are replaced by new particles from the respective sources at optimal conditions to help to preserve the average beam dimension.

THE CIRCULAR RADIO-FREQUENCY STORAGE RING

A conventional magnetic storage ring does not have the capability to store a beam at the current and dimension as specified above. One needs the development of a new concept. This is the Circular Radio-Frequency storage ring. The device has a toroidal shape, is similar to a four-rod RFQ with constant aperture closed mechanically on itself as shown in Fig. 4, but electrically open so it is equivalent to a long unbounded transport. An rf excitation with wavelength λ is applied across the four rods. The motion of an ion is described by the RFQ parameter

$$B_0 \;=\; (2\, Ze\, V_0 / Am_0\, c^2)\, (\lambda / b)^2 \qquad (4)$$

where V_0 is the peak rf voltage, $m_0\, c^2$ the proton rest energy, and b the minor radius of the structure.

As in the ordinary linear RFQ (Staples, 1992), the focussing is alternating with a periodicity $\Lambda = \beta\lambda$. The value B_0 = 6.809 gives a phase advance per period of 90°, and an average amplitude lattice function $\beta_L \sim 1.4\, \Lambda$. If ε denotes the beam emittance, with the same value in the horizontal and vertical direction of oscillation, the average beam radius is $a = (\varepsilon\beta_L)^{1/2}$, which of course is to be smaller than aperture radius b. Because in our case $\beta \sim 0.011$, the focussing period is very short, of few centimeters, compared to a meter or more in a conventional magnetic storage ring. At the same time the transverse beam dimensions are also considerably smaller.

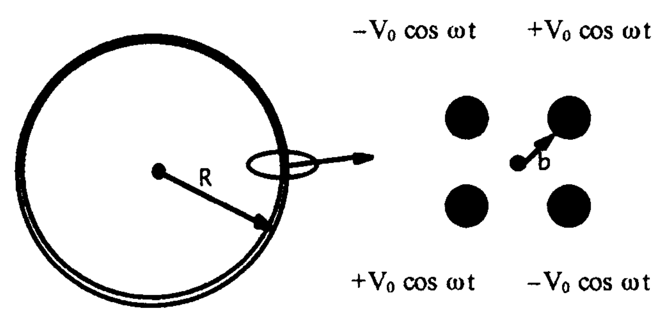


Figure 4. The Circular RFQ Storage Ring

In the approximation that the periodicity Λ is much smaller than the major radius of curvature R, usually satisfied, the trajectory of an ion is bent by the effect of the rf field. It follows closely the curvature of the rods, with an average outward radial offset (Ruggiero, 2000)

$$x_{off} = 33.6\, \Lambda^2 / \pi^2\, R \qquad (5)$$

A dispersion of the same magnitude is also introduced in both planes of oscillations. As long as $x_{off} << b$, the beam is within the aperture, and remains confined without the need of an external bending magnet.

As in the ordinary linear RFQ, also in the CRFQ storage ring one may expect the transport of considerably higher beam intensity. The motion is space-charge dominated when the phase advance per period is appreciably depressed from the zero-current value of 90°. The space-charge effect is measured by the following parameter (Ruggiero, 2000a)

$$\Delta \;=\; 2\, N\, Z^2\, r_0\, \lambda^2 / A\, \pi\, S\, C \qquad (6)$$

where N is the total number of circulating ions, and r_0 = 1.535 x 10^{-18} m the classical proton radius. A depression of the phase advance down to 45° corresponds to the limit $\Delta \sim 0.044$. Note that Eq. (6) sets a limit on the volume density

$$\delta \;=\; N / SC \;=\; (4.5 \times 10^{14}\ \text{cm}^{-3} / \lambda_{cm}^2)\, (A/Z^2) \qquad (7)$$

Since we can also write

$$\mathcal{L} = \;\eta\, \beta c\, \delta_p\, \delta_B\, SC \qquad (8)$$

we determine that in order to obtain the luminosity required for a total of 10 kW of fusion power, we need to satisfy

$$SC / \lambda^4 \;\sim\; 100 / \text{cm}. \qquad (9)$$

We shall see the consequences of these relations next.

REQUIREMENTS OF WARM-BEAM COLLISION IN THE CRFQ STORAGE RING

Even with a more advanced storage ring as the CRFQ, that allows higher beam intensity and smaller beam dimensions, there are significant engineering requirements which are difficult to be achieved with today's technology. All the equations in the above sections can be combined together to evaluate the design. For instance, Fig. 5 gives the storage ring radius R versus the excitation frequency for different beam emittance ε. A value of practical interest is R = 1m. Inspection of the figure shows that the required excitation frequency ranges between 300 and 100,000 GHz, very large indeed. The number of ions of Boron required is shown in Fig. 6. In the same frequency range, the intensity varies between 10^{10} and 10^{15}; thus the beam intensity required is not necessarily an issue. The ratio $b/2a$ of the aperture radius to the beam size is plotted in Fig. 7. Since the beam is to be entirely accommodated within the aperture, this ratio should be larger than one. This requires a small beam emittance: $\varepsilon < 0.001\ \pi$ mm-mrad. The excitation rf peak voltage and power are not necessarily issues. They are shown in Fig.s 8 and 9. Typical values are around one or few hundreds of kVolt, and at most few Watts. On the other end, considering the small dimension b of the CRFQ, the internal electric field is large, and can easily exceed the surface practical limit.

The selection of a very large excitation frequency, and consequently of the very small transverse dimension of the CRFQ, are serious technology challenges that can hardly be development of more futuristic technology.

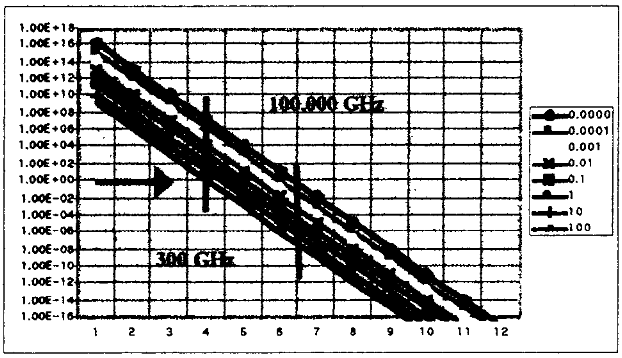


Figure 5. Ring Radius R (m) vs. Frequency (MHz)

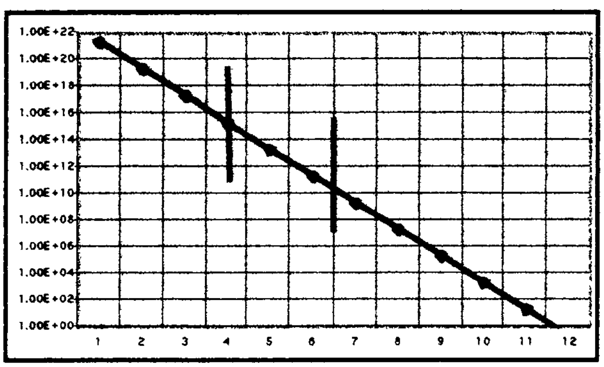


Figure 6. Number of Boron Ions vs. Frequency (MHz)

CAUSES OF PARTICLE LOSSES

Our intent is to minimize power dissipated for the operation of the device to a small fraction of the total power produced by fusion. Also, it is important to minimize the loss of beam intensity and size to concurrent phenomena other than fusion. It is relatively easy to list the channels of losses.

Single-Beam. Ring imperfections can be controlled to eliminate beam loss by assigning error tolerances during the manufacturing. The Space-Charge effects are of no concern, since they have already been included in the analysis of the CRFQ. There are no nuclear reactions and no fusion events between particles of the same beam because of the very small energy difference. Mostly serious is Intra-Beam Scattering (IBS), that is Coulomb scattering. There are two loss mechanisms. One is made of single-event large-angle scattering that causes immediate removal of the particle from the beam after hitting the physical aperture. The other is a sequence of small-angle scattering that may lead to an emittance growth, increase of the beam size, and a loss of luminosity. IBS is a well understood phenomena in particle accelerators and storage rings (Piwinski, 1974). A complete theory is available also for the CRFQ storage ring (Ruggiero, 2000b). The theory predicts a growth or reduction of the beam emittance ε and momentum spread δ which depends linearly with the beam intensity and in a very complicated way with the emittance and momentum spread itself, according to

$$d\delta / dt = N f(\varepsilon, \delta) \tag{10}$$

$$d\varepsilon / dt = N g(\varepsilon, \delta) \tag{11}$$

Since one operates below the transition energy of the storage ring, one can prove that an equilibrium is reached when $f(\varepsilon, \delta) = g(\varepsilon, \delta) = 0$. The thermal-dynamical equilibrium is reached when the transverse and longitudinal temperature within the beam have relaxed and become equal. Though the relaxation rates depend on the beam intensity, the equilibrium does not, and is given by $\delta^2 = \varepsilon / \beta_L$. The required beam momentum spread at the equilibrium is displayed in Fig. 10. It is seen that at very most a spread of 10% may be required. Observe that if $\varepsilon > \delta^2 \beta_L$ the beam emittance decreases during the relaxation process, enhancing the luminosity at cost of increasing the ion momentum spread. The relaxation times are then to be compared to the fusion time τ. If they are large enough, every time a pair of ions fuse they are replaced by the ion sources with others with small initial spreads.

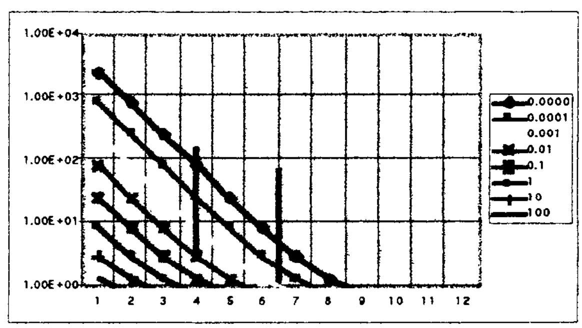


Figure 7. The ratio $b/2a$ vs. Frequency (MHz)

Beam-Beam. Ring imperfections are not relevant in this case. Space-charge effects between the two beams should be included, but, because of the low energy, they are equivalent to the single-beam space-charge effects, actually extending only over the fraction η of the ring circumference. As we have already discussed in one of the previous section, the colliding beam method has the advantages to select the two beam energies carefully to avoid all other nuclear reactions except the desired fusion reactions. The only reaction that cannot be avoided is again Coulomb scattering, or Beam-Beam Scattering (BBS). Similarly to the single-beam case, also in the beam-beam interaction large-angle scattering causes instant particle loss, whereas small-angle scattering leads to a growth of the beam size and thus to a reduction of luminosity. In analogy to IBS, a complete theory of BBS (Ruggiero, 2000b) has been formulated to determine the beam emittance and momentum spread growth during interaction. The growth rates are given by

$$d\varepsilon / dt = 4 \pi k L \beta_L \tag{12}$$
$$d\delta^2 / dt = (d\varepsilon / dt)\, \varepsilon\, A_1^2 / (A_p + A_B)^2 \beta_L^2 \tag{13}$$

with

$$k = 2 N Z_p^2 Z_B^2 r_0^2 c \eta A_2 / S C \beta^3 A_1 (A_p + A_B)^2 \tag{14}$$

The diffusion rates due to BBS are displayed in Fig. 11. The emittance growth rate does not depend on the initial emittance value. The momentum spread growth rate depends linearly with the emittance. The case shown in Fig. 11 corresponds to ε = 0.001 π mm-mrad. It is seen that it is possible to control the momentum spread growth, but the beam emittance will just explode.

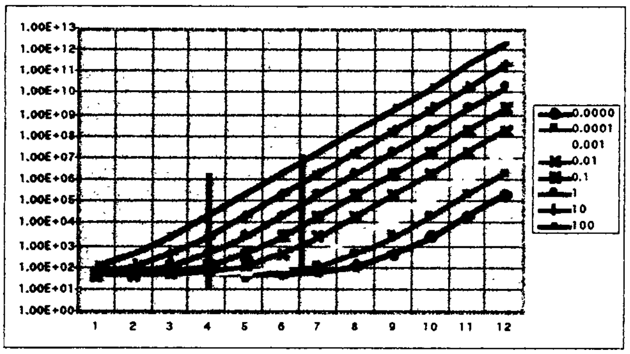


Figure 8. Peak Voltage (kVolt) vs. Frequency (MHz)

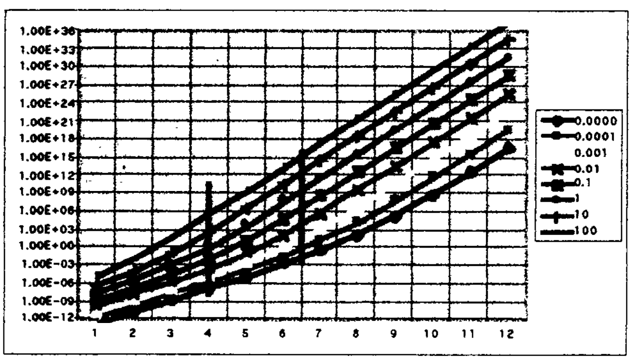


Figure 9. rf Power (Watt) vs. Frequency (MHz)

<u>Vacuum Residual Gas Effects.</u> Molecular dissociation, atomic excitation and ionization cause energy loss and the creation of thermal ions and electrons. On the other end, no nuclear reactions are expected (including fusion). It is determined that a vacuum pressure of 10^{-7} torr is sufficient and necessary to control all effects on beam stability. Multiple and single Coulomb scattering lifetimes are displayed in Fig.s 12 and 13 where they are compared to the fusion lifetime. Of course, no matter how small are the losses, they can be amplified by wall-desorption effects when errand ions hit the rods or the vacuum tank. Thus it is important to treat and condition the vacuum environment.

The α-particles generated in the fusion events are supposed to be decelerated in the reactor vessel and eventually be absorbed in the electrodes. On the other end, it is not clear what are the effects of the α's when desorbing from the material they penetrate.

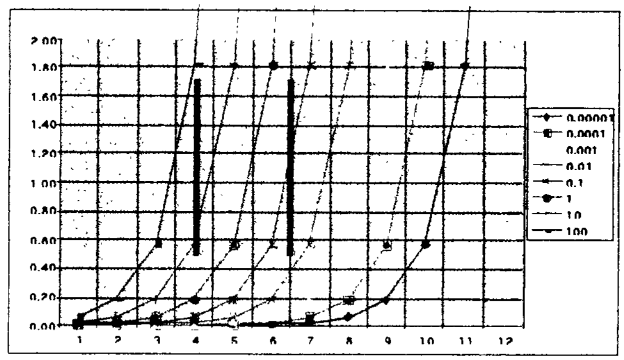


Figure 10. Beam Momentum Spread at Thermal-Dynamical Equilibrium (IBS)

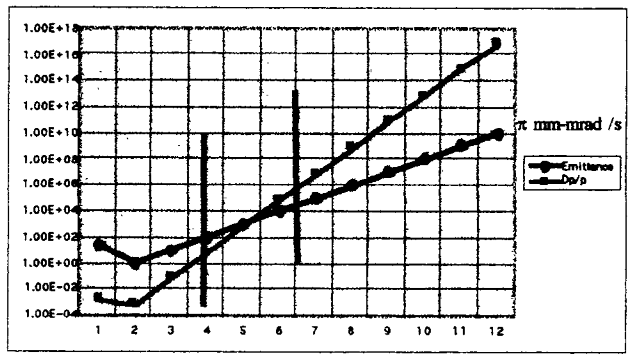


Figure 11. Beam-Beam Scattering Diffusion Rates

<u>Summary.</u> A 10-kWatt Nuclear Fusion device involving two small storage and intersecting rings (R ~ 1m) requires a novel concept of low-energy ion storage ring. The Circular Radio-Frequency Quadrupole storage ring (CRFQ) allows very short periodicity of focussing, very small beam dimensions, high beam intensity, and considerably lower susceptibility to errors, which makes the motion of ions in the device very stable. The rf excitation of the CRFQ has a very large frequency requirement (of several hundreds and even thousands of GHz). The device can be made even smaller and more compact by adopting higher excitation frequency. But this requires also correspondingly the development of mechanical and electrical engineering. Is this possible? How far can one extrapolate? What are the tolerances?

The most crucial concern is the Coulomb scattering among ions in the same beam (IBS), and between the two colliding beams (BBS). The theory of these effects is well developed, understood, and at hand for particle accelerators. The use of the CRFQ actually softens considerably these problems. A thermal-dynamical equilibrium exists. IBS can be controlled by adjusting the relative spreads of momenta. The BBS is calculable but it is more problematic. Obviously these combined effects are to be investigated further.

No other physical limitations are predicted. The method of colliding beams of Boron and Proton, to obtain a modest amount of Nuclear Fusion Power, in small size storage and intersecting rings has some potentials and possibilities. In our opinion it deserves a more intense investigation than the one summarized in this paper.

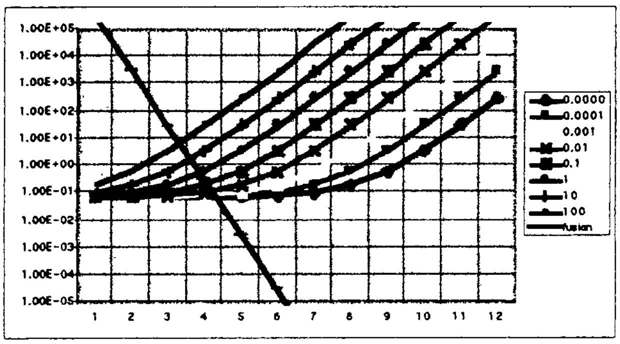


Figure 12. Multiple Coulomb Scattering Lifetime (s) and Fusion Lifetime (s)

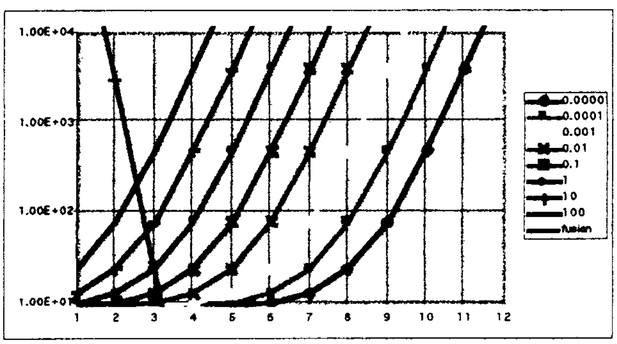


Figure 13. Single Coulomb Scattering Lifetime (s) and Fusion Lifetime (s)

CRYSTALLINE BEAMS AND STRUCTURES

Crystalline Structures have already been observed in ion traps (Walther, 1993), Crystalline Beams, that are organized structures moving in a storage ring, still wait for an experimental demonstration. A Crystalline Beam is a state of matter which can be obtained from diluted ion beams in low-energy storage rings with the application of a very fast cooling technique, namely Electron and/or Laser Cooling. If enough internal energy is removed at a sufficient large rate, the ions will take a rigid configuration where they are equally spaced from each other. The theory of Crystalline Beams does exist and predicts that organized beams can be obtained in storage rings with very high periodicity and strong focussing (Ruggiero, 1994, 1999b). The CRFQ storage ring is the ideal candidate. In its ground state, a Crystalline Beam is made of a number of *strings* placed parallel to each other symmetrically around the beam axis, as shown in Fig. 14. Because of the left-right and up-down symmetry the number of *strings* is a binary number, that is $m = 2^p$ where p is called the *bifurcation* order. Particles are equally spaced on each *string* and the spacing λ_s is the same for all *strings*. There is a range of spacing $\lambda_1 > \lambda_s > \lambda_2$ in which a particular structure, characterized by the number m of *string* exists. Typically $\lambda_1 \sim 2\ \lambda_2$, where $\lambda_2 \sim \lambda_c\ c_t$ denotes the stability limit, where

$$\lambda_c = (Z^2 r_0 R^2 / A \beta^2)^{1/3} \qquad (15)$$

is the critical spacing, and $c_t \sim (2 / \nu^2)^{1/3}$, a form factor which measures the distance of the zero-current operating tune ν of the storage ring from a lower half-integral structural resonance that the beam will cross under the depression caused by space-charge forces.

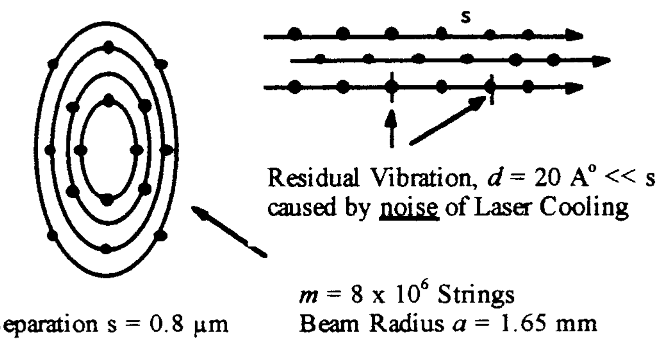


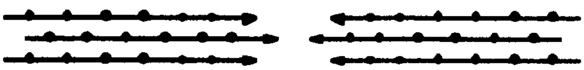
Figure 14. Multiple-String Crystalline Beam

COLLISION OF ORGANIZED BEAMS

To alleviate the engineering limitations and the physical concerns, we propose to reach our goal with (a) Beam Crystallization, and (b) Colliding Crystalline Beams. The first topic is very delicate and sophisticated subjetc still waiting to be demonstrated. It needs a new ingredient: a fast cooling technique. The second topic is of course provocative and it may sound very futuristic.

Figure 15 shows the geometry and luminosity of colliding Organized Beams, that is each beam is made of a number m of parallel *strings* equally spaced, which best represents a Crystalline Beam, discussed above.

The total luminosity $\mathcal{L}_0$ is m times the luminosity $\mathcal{L}_s$ of two strings paired together so to collide head-on with each other. Each pair of *strings* is made of n_p and n_B ions of proton and boron. As usual, $f_0 = \beta c / C$ is the revolution frequency in the respective storage ring. We assume again that the storage rings have the same geometry and circumference $C = 2\pi R$, and that the energy of the two beams is adjusted so that they travel at the same speed βc. The fraction of the ring circumference where the two beams collide is still denoted by η. The common cross section of the two *strings* colliding is now πd^2, to be compared to the effective common cross section of the two beams $S = \pi a^2$. The number of *strings* $m = S / \pi s^2$, with s the separation between *strings* which is also the longitudinal separation. The total number of circulating ions $N_{pB} = m\, n_{pB}$.



$$\mathcal{L}_o = \eta\, m\, n_p\, n_B\, f_0 / \pi d^2 = m\, \mathcal{L}_s$$

Figure 15. Colliding Organized Beams

Consider the case of a small storage ring with C = 10m, so that f_0 = 328 kHz. A typical ion separation that one may expect in a Crystalline Beam is s = 0.8 μm. The effective radius of a *string* is determined by the ultimate noise of the cooling system, and one can expect d = 20 A°. Denoting with $\mathcal{L}_w$ the equivalent "warm" beam luminosity given in Fig. 3, the actual luminosity of Organized Beams is

$$\mathcal{L}_0 = \mathcal{L}_w\, (s/d)^2 \sim 1.6 \times 10^5\, \mathcal{L}_w \qquad (16)$$

That is an enhancement of several orders of magnitude.

With our parameters, the luminosity per pair of colliding *strings* is $\mathcal{L}_s \sim 1 \times 10^{32}$ cm^{-2} s^{-1}. In order to reach the required total luminosity of $\mathcal{L}_0 = 0.8 \times 10^{39}$ cm^{-2} s^{-1}, we need $m = 8 \times 10^6$ parallel *strings* in each beam. This is equivalent to the *bifurcation* order $p = 23$. The periodicity of the CRFQ storage ring (the number of focussing periods per revolution) is to be at least equal to or larger than this. An rf excitation of few hundred MHz, which over a circumference of 10m gives few thousand periods, is then adequate. The number of ions per *string* is then 1.2×10^7, and the total number of ions in each beam is 5.0×10^{13}. The resulting depletion rate is then 144 s^{-1}, that is a fusion lifetime of only 6 millisecond, about two thousand revolutions.

LASER COOLING AND SYMPATHETIC COOLING

For the ion beam to freeze down to a ground state of a crystalline structure, fast cooling is to be supplied to remove internal energy. The cooling rate is to be sufficiently large and effective, with minimum noise at equilibrium. Two techniques are available: Electron and Laser Cooling. In the former the ions to be cooled are fully stripped, but the final temperature depends on the electron beam temperature; moreover there is an appreciable chance that ions are lost by recombining with the electrons. Laser Cooling is faster and more effective, but requires that ions have orbiting electrons. When two partially ionized beams collide with each other, the ionization process dominates the fusion events, so that the presence of electrons is an impediment to an efficient production of power from nuclear fusion events. There are thus two alternatives: the first is to rely exclusively on Electron Cooling; the second is to make use of Sympathetic Cooling. In the second option ions are fully stripped and are cooled by exchanging heat by interacting with a stationary plasma of Be^+ or Mg^+ confined in an ion trap. The ion trap is then inserted on one side of the CRFQ storage ring, away from the interaction region, and will occupy only a modest fraction of the ring circumference. It is not the purpose of this paper to go further in the details of cooling techniques. We note here simply that the amount of energy removed during the cooling process is modest, essentially given by P_{cool} = (675 keV) (ε / β_L) I_{pB} ~ 10 Watts.

COLLIDING CRYSTALLINE BEAMS

What happens when two Strings collide with each other? Are they destroyed? It depends on how effective is Cooling and the Procedure for storing, cooling and colliding beams. It has been demonstrated (Haffmans et al., 1995) that there is a stable configuration of two *strings* colliding where the ion trajectories take the shape of a "pretzel", as shown in Fig. 16.

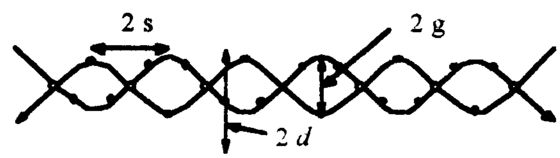


Figure 16. Pair of Strings in Collision

Also, if 2g is the amplitude of the "pretzel", the following stability condition is to be satisfied

$$g > (\beta\lambda \;/\; \pi R)\, s \qquad (17)$$

In order for ions to scatter with each other (and fuse) the following scaling is to be satisfied,

$$s > d > g > \text{Ion Size} \qquad (18)$$

THE OPERATIONAL PROCEDURE

1. At the start, the two storage rings are continuously filled by the Ion Sources at currents corresponding to the depletion rate of 55 s^{-1} that is I_{pB} = 1.15 mA-particle, equal to 2×10^{11} ions per turn. The ions are completely stripped.
2. The two counter-moving beams are made to collide head-on from the start and kept colliding continuously.
3. At the same time, Electron Cooling (or Sympathetic Cooling) is also continuously applied to both beams at the rate of 300 s^{-1} yielding an emittance reduction in few hundreds revolutions.
4. Crystalline Beams are formed at the same.
5. During the intensity build-up, initially there are fewer fusion events and smaller number of *Strings*. As the intensity increases, the number of *Strings* and the fusion events also increase, until saturation is reached, when the rate of ions depletion equals the Source current.

6. Every time a particle is removed (depleted) after fusion, it is replaced by a new one from the Source, immediately cooled, and inserted in the Crystalline Beam.

7. The process of particle removal and addition is slow enough to avoid disruption and to preserve the Crystalline Structure.

8. The stability of Crystalline Beams at Collision is maintained with the same assumptions and conditions.

ENERGY BALANCE AND EFFICIENCY

The device produces a total nuclear fusion power of 10 kW. Only a fraction of this is actually available to an external load. Some power will be dissipated for the operation of the plant itself. The following is a not-optimized list of dissipated power items:

Beam Power	0.78 kW
Beam Loss Allowance (30%)	0.22
Ion Sources	1.00
RF Power for CRFQ	1.34
Laser / Electron Cooling	0.10
Computer	0.50
Miscellaneous (vacuum, diagnostic, ...)	1.00

According to this estimate, the total dissipated power amounts to 4.94 kW, with a positive balance of 5.06 kW, and an efficiency of about 50%.

RESEARCH AND DEVELOPMENT

Below we list the crucial steps to undertake for a successful demonstration of the nuclear device:

A. Design, build, demonstrate a CRFQ prototype.
B. Develop proton and fully stripped boron ion sources
C. Reach Space-Charge Limit in the CRFQ with protons
D. Reach Space-Charge Limit in the CRFQ with Boron
E. Experiment with Electron Cooling
F. Experiment with Sympathetic Cooling (Ion Traps)
G. Crystallization of Proton Beam
H. Crystallization of Boron Beam
I. Fabrication of two intersecting CRFQ's: for p and B
J. Experiment with collision of "warm" beams
K. Cooling of Colliding Beams
L. Crystallization of both Beams during Collision
M. Preliminary detection of Nuclear Fusion events
N. Develop Reactor Vessel around Collision Region
O. Efficiency Studies

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REFERENCES

Lidsky, L.M., 1983, "The Trouble with Fusion", Technology Review. Edited by M.I.T.

Ruggiero, A.G., 1992, "Nuclear Fusion of Protons with Ions of Boron", Internal Report BNL-47989.

Ruggiero, A.G., 1993a, Proceedings of the Particle Accelerator Conference, Washington D.C., Vol. 1, p. 700.

Ruggiero, A.G., 1993b, *Il Nuovo Cimento*, Vol. 106 A, N. 12, p. 1959.

Ruggiero, A.G., 1998a, "Concept of a Nuclear Plant based on the Fusion Reaction of Protons with Ions of Boron", Internal Report BNL-AGS/AD/Tech. Note 478.

Ruggiero, A.G., 1998b, "The Circular RFQ Storage Ring", Internal Report BNL-65920.

Ruggiero, A.G., 1998c, Workshop on Nonlinear and Collective Phenomena in Beam Physics, Arcidosso, Italy, AIP Conf. Proc. 468, p. 244.

Ruggiero, A.G., 1999a, Proceedings of the Particle Accelerator Conference, New York, N.Y., p. 3731.

Wertheim, Germany, 1988, Workshop on Crystalline Ion Beams, GSI-89-10. Editors R.W. Hasse, I. Hofmann and D. Liesen.

Montreux, Switzerland, 1993, Beam Cooling and Related Topics, CERN 94-03. Editor J. Bosser.

Erice, Italy, 1995, Workshop on Crystalline Beams and Related Issues, The Science and Culture Science – Physics. World Scientific. Editors D.M. Maletic and A.G. Ruggiero.

Mitchell, T.B. et al., 1999, "Crystalline Order in Strongly-Coupled Ion-Plasmas", Workshop on Non-neutral Plasma Physics III, Princeton, New Jersey, AIP Conf. Proc. 498, p. 353.

Ajzenberg-Selove, F. and Busch, C.L., 1980, *Nucl. Phy.* A, **336**, 73.

Becker, H.W. et al., 1987, *Z. Phys. A* – Atomic Nuclei **327**, 341-355.

Blewett, J.P., 1974, "Fusion Reactions in Colliding Beams", Proc. IX-th Inter. Conf. On High Energy Accelerators, page 531. Stanford, California.

Maglich, B.C. and Chang, T-F, 1993, *Phys. Rev. Letters*, **70**, no. 3, page 299.

Staples, J.W., 1992, "RFQ's – An Introduction". The Physics of Particle Accelerators. AIP Conf. Proc. 249, Vol. II, page 1483.

Ruggiero, A.G., 2000a, "Beam Dynamics in the Circular RFQ Storage Ring", Paper in preparation. Brookhaven National Laboratory (1999).

Piwinski, A., 1974, "Intra-Beam Scattering", Proc. IX-th Inter. Conf. On High Energy Accelerators, page 405. Stanford, California.

Ruggiero, A.G., 2000b, "Intra-Beam and Beam-Beam Scattering in the Circular RFQ Storage Ring", Paper in preparation. Brookhaven National Laboratory (1999).

Walther, H., 1993, *Advances in At. Mol. And Opt. Physics*, **31**, 137.

Ruggiero, A.G., 1994, "Crystalline Beams: Theory, Experiments, and Proposals", Workshop on Quantum-Like Models and Coherent Effects. Erice, Italy. The Science and Culture Science – Physics. World Scientific. Editors R. Fedele and P.K. Shukla.

Ruggiero, A.G., 1999b, "Crystalline Beams", to appear in the Proc. of the ICFA Workshop on the Physics of High Brightness Beams , UCLA, California.

Haffmans, A.F., et al., 1995, "Colliding Crystalline Beams", Proc. Particle Accelerator Conference, Washington, D.C., p. 3329.

